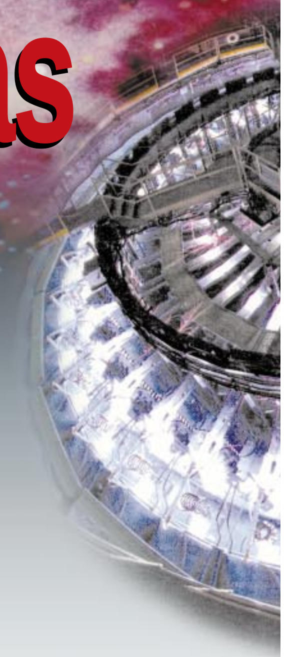
Duplicating the Plasmas of Distant Stars



Groundbreaking Livermore experiments are strengthening our understanding of matter at extreme conditions. The results are aiding researchers in both astronomy and nuclear stockpile stewardship.

AT first glance, it might seem odd for weapons scientists to be looking to the stars for information and inspiration. However, the physical processes of stars have long been of interest to Lawrence Livermore researchers because the prime stellar energy mechanism, thermonuclear fusion, lies at the very heart of the Laboratory's national security mission.

For many years, Livermore researchers have played a major role in astrophysics by applying their expertise in high-energy-density physics and computer modeling of atomic processes. The astronomical community has benefited enormously from Livermore contributions, including the search for "dark matter" in the universe, laser guide star optics that sharpen terrestrial astronomical viewing, instruments to map the moon in unprecedented detail with the Clementine satellite, advanced x-ray spectrographs for U.S. and European spacecraft, and theoretical models of supernovae and other stars.

Livermore researchers are again breaking new ground, creating in the laboratory the same kinds of extremely hot plasmas (gases containing electrically charged particles) found in distant stars and comparing the results to models. The data from these experiments will help strengthen the theory of matter at extreme conditions. In turn, these models will help scientists gain a more complete understanding of the birth and evolution of stars, galaxies, and the universe itself.

Closer to home, the new experimental techniques, improved codes, and diagnostics developed for the tests are aiding stockpile stewardship, the Department of Energy's program to keep the nation's aging arsenal of nuclear weapons safe, secure, and reliable in the absence of underground nuclear testing. The expertise gained will also aid experiments on the National Ignition Facility (NIF), the giant laser now under construction at Livermore as a key stockpile stewardship facility.

"There's a tremendous amount of overlap between the kinds of physics involved in astrophysical systems and those in nuclear weapon systems," says Bill Goldstein, acting Associate Director of the Physics Directorate and leader of the Laboratory's effort to provide the most modern validated physics models for stockpile stewardship. Even when an astronomical process is not exactly duplicated by a nuclear weapon, studying the phenomenon is useful to ensuring that Livermore atomic models are versatile and valid in different environments, he says.

Many astrophysicists, Goldstein says, become weapon scientists because the fields involve similar physics. He also notes that the Accelerated Strategic Computing Initiative (ASCI), DOE's program to significantly advance computer simulations of nuclear weapon performance, has formed alliances with several universities to model supernovae in unprecedented detail.

Paul Springer, Livermore physicist and stellar plasma experiment leader, observes that the same computer models, as well as the same diagnostic equipment, are used for understanding atomic processes at work in both weapons and stars. Springer is a member of Livermore's High Energy Density and Space Technology Division, which studies the properties of matter at extreme conditions of density and temperature.

The division's work includes weapons physics experiments, diagnostic instrument development, advanced modeling codes, as well as theoretical, laboratory, and observational astrophysics. Aiding the research are numerous collaborations with other DOE national laboratories and astronomy departments of leading universities and observatories.

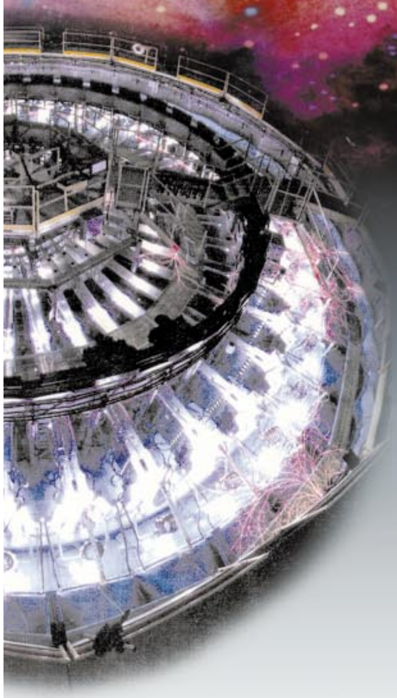


Figure 1. The Livermore experiments re-creating stellar plasmas were done at the 500-kilojoule Saturn accelerator at Sandia National Laboratories.

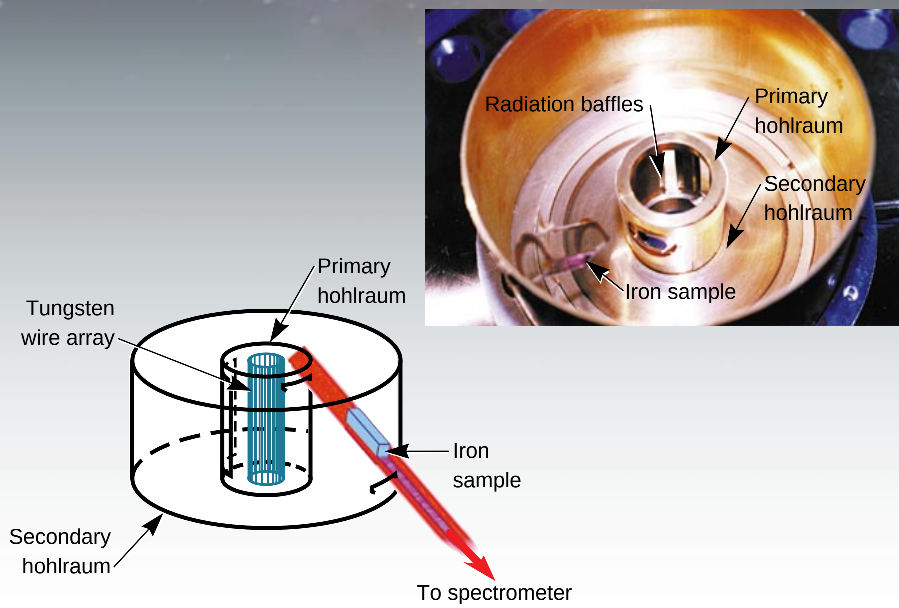


Figure 2. Schematic diagram and photograph of the apparatus used for laboratory astrophysics experiments.The stellar experiments confine an intense x-ray flux to a metal case (called a hohlraum) to improve the radiation's spatial uniformity and heat the case to temperatures exceeding 1 million degrees centigrade. Energy from the primary hohlraum flows through an adjustable baffle into a gold-plated secondary hohlraum, which in turn heats the 1- centimeter-long sample to create a plasma. The illumination of the target is analyzed by a spectrometer.

Focusing on Three Kinds of Stars

Springer's experimental program focuses on three classes of astronomical objects: cepheids (big pulsating stars), supernovae (the brightest objects in the universe), and stars that generate x rays through a process called accretion. A key aspect of the experiments is testing advanced Livermore atomic models—OPAL for the cepheid and supernova experiments, and LXSS for the x-ray tests. Unlike older codes that simplify atomic processes, these codes were built for accuracy and completeness.

Livermore experiments make use of the pulsed-power facilities at Sandia National Laboratories in Albuquerque, New Mexico. Until the completion of NIF in 2003, Sandia's facilities are unique in their ability to create the low-density plasmas typical of many star systems. Livermore researchers have used these facilities during the past two years for stockpile stewardship studies, such as determining the radiation effects on warhead components and testing three-dimensional computer codes that simulate nuclear weapon effects. Until Springer's experiments, the facilities had never been exploited for astrophysics research.

The cepheid and supernova experiments were conducted at Sandia's 500-kilojoule Saturn accelerator (Figure 1), while experiments duplicating x-ray objects' stellar plasmas are planned for Sandia's more powerful Z-Machine, rated at 2,000 kilojoules of energy. Diagnostic equipment for the experiments, including advanced spectrometers, is built at Livermore and transported to Sandia.

The Sandia machines use large banks of capacitors to build and store electrical charges, then simultaneously discharge them in a fraction of a second. The electrical pulse produces a powerful electromagnetic field. A circular array of fine tungsten wires, each a few micrometers in diameter, is ionized into a hot plasma by the compressive force of the electromagnetic field.

Implosion of the wire causes the release of hundreds of thousands of joules of x-ray energy. The intense x-ray energy is confined within a metal case (called a hohlraum), thereby enhancing the spatial uniformity of the radiation and heating the case to temperatures exceeding 1 million degrees centigrade. Energy from the primary hohlraum flows through an adjustable baffle into a gold-plated secondary hohlraum, which in turn heats a target to create a plasma. (Figure 2). This x-ray target "illumination" is captured and analyzed by a spectrometer. The data are then compared to results predicted by the Livermore atomic models. The experiments thus serve to both validate the codes and refine them.

Springer notes that the experiments require months of preparation, both in the design of the experiment and in the selection and occasional manufacturing of diagnostic equipment. The experiments benefit from researchers' accumulated expertise in designing targets for Livermore lasers, diagnosing underground nuclear tests at the Nevada Test Site, and working with pulsed-power facilities.

Understanding Pulsating Stars

When massive stars evolve from blue supergiants to yellow supergiants, they can temporarily become extremely luminous pulsating stars called cepheid variables. There are only about 700 known cepheids in our galaxy; the best known is the North Star, Polaris.

What fascinates astronomers about cepheids is their regular variation in brightness, with periods ranging from 1 to 70 days. A longer pulsation period means an intrinsically brighter (hotter) star. Consequently, cepheids give astronomers a means of measuring distances to stars in other galaxies. If the pulsation period is known, its true luminosity can be deduced. By comparing the intrinsic brightness with the average brightness of the star, as seen from Earth, the actual distance to the star (and its parent galaxy) can be calculated. The technique is similar to judging the distance to a lighthouse at night based on its brightness as seen from a boat. In this way, cepheids serve as what astronomers term a "standard candle" for distances up to 60 million light years.

Accurately determining the star's intrinsic luminosity depends on energy transport models, or opacity (see the box at the right). Astronomical observations of cepheids had pointed to larger stellar masses than those predicted by the existing opacity model. In 1992, however, Livermore's OPAL opacity code resolved the quandary by including more accurately the opacity effects of elements heavier than helium (called "metals" by astronomers) such as iron. The new stellar models now calculate stellar masses in good agreement with the observations.

"We know now that cepheids pulsate because of the dominant role played by iron," says Springer. He compares the stars to a covered pot of water being heated that builds up heat and generates steam that lifts the lid, releasing the pressure. The lid falls back, and the process begins again. As cepheids contract, they become hotter because of iron ions blocking the transmission of

OPAL Tracks the Transfer of Energy

The physical properties of stars depend upon the transport of energy from their nuclear cores to their surface. Although energy can be transferred out from the center by conduction and convection, radiation transport is the most important mechanism. In turn, the transport of photons depends on the transparency of the intervening matter, termed the radiative opacity. Consequently, opacity plays a key role in determining the evolution, luminosity, and instabilities of stars and even the eventual fate of the universe.

Acquiring a better understanding of opacities is a key goal of the Department of Energy's Stockpile Stewardship Program to keep America's nuclear stockpile safe and reliable. Stellar opacity is involved primarily with lighter elements, while opacity of nuclear weapons plasmas focuses on heavier elements like uranium; yet, the physics in both cases is similar.

It is extremely difficult to measure plasma opacities directly; researchers must rely on a detailed computer model to calculate opacities. However, "Modeling opacity is one of the more difficult tasks in physics," says Livermore physicist Bill Goldstein. In addition to temperature, density, and composition of a plasma, opacity depends on the many atomic absorption processes possible within every ion. Ions continually jump from one energy state to another, each with its own characteristic spectral absorption line. (Iron, with its 26 electrons, can have literally millions of different energy states and corresponding spectral lines.)

Livermore physicists Forrest Rogers, Carlos Iglesias, and Brian Wilson built a new model of stellar opacity called OPAL. Cited more than 500 times in the past few years in astrophysical research papers, OPAL has had an enormous influence. It achieved widespread acceptance earlier in the decade when it helped to resolve longstanding quandaries concerning pulsating stars.

"OPAL is accurate, thorough, and has a proper consideration for physics," says Livermore physicist Paul Springer. "It avoids many of the approximations and simplifying assumptions used in earlier codes." In particular, the code accurately treats the myriad energy transitions in iron. The role of these transitions was previously overlooked in blocking radiation, says Iglesias. As a result, the new OPAL calculations show that iron, the most abundant heavy element in a star, can significantly impede radiation flow and therefore plays a huge role in the properties of a star.

Over the years, OPAL has been refined through experiments on Livermore's Nova laser, which gave the first measurement of the opacity of iron, and more recently, in experiments at Sandia National Laboratories in Albuquerque, which gave the first iron opacity measurements at stellar conditions.

heat. To release the heat, the cepheids expand, radiating the energy away and, in the process, becoming cooler and larger.

Given the complexity of stellar models, it was crucial to validate OPAL's model of cepheid opacities directly in the laboratory. In separate experiments, Livermore physicists Luiz Da Silva, Springer, and others had previously verified data and atomic models in OPAL using Livermore's Nova laser. Although these measurements provided opacity data at astrophysically relevant temperatures, these plasmas were too dense and too short-lived to simulate those of cepheids.

Springer turned to Sandia's 500-kilojoule Saturn facility to more accurately duplicate the plasmas. To achieve plasma equilibrium and meet the goal of 100 times lower density (10^{-4} grams per cubic centimeter), the iron foil target used on Nova was increased in length from 0.03 to 1.0 centimeter, and radiation fields lasting tens of nanoseconds (billionths of a second), some 10 times longer than was possible on Nova, were generated. In addition, a 10-fold improvement in spectral resolution was achieved using an advanced spectrometer built by Livermore engineer Grant Hill (Figure 3). The experiment provided the first direct test of stellar opacities, verifying OPAL's atomic model and helping to refine it.

Simulating Exploding Stars

Building upon the success of the cepheid experiments, Springer's team duplicated plasmas at the Saturn facility resembling those created by one of the most spectacular phenomena in the universe, supernovae. A longtime focus of Livermore interest, supernova explosions leave behind gaseous nebulae, neutron stars, or black holes, objects so dense that even light cannot escape their gravity. In addition, supernovae are believed to produce nearly all the elements in the universe heavier than helium, and their occurrences in or near clouds of cold, molecular gas may trigger the formation of stars.

The Livermore experiments produced a miniature, low-density, expanding (200 kilometers per second) plasma similar to those detected on supernovae. In both cases, the rapid expansion causes spectroscopic absorption lines to be blurred together, significantly complicating calculations of opacity. The experiments again verified OPAL's atomic model, this time for dealing with expanding plasmas, and provided data to benchmark all simulation codes used to model the transport of radiation through rapidly expanding plasma.

Springer's experiments were designed to approximate conditions in the expanding debris (ejecta) being blown off Type Ia supernovae. These explosions result from old, dead stars called white dwarfs, which have the mass of the sun but a size comparable to that of Earth. In most cases, the white dwarf consumes matter from an evolving companion star via a process called accretion, one of the dominant energy conversion processes in the universe. Once the white dwarf reaches a mass 1.4 times that of the sun, a thermonuclear explosion ensues that rips it apart, and the entire star is expelled at velocities reaching one-tenth the speed of light.

Type Ia supernovae have played a central role in recent results obtained by cosmologists attempting to determine the curvature of space. The results obtained so far, says Livermore astrophysicist Ron Eastman, point to the exciting possibility that in the distant

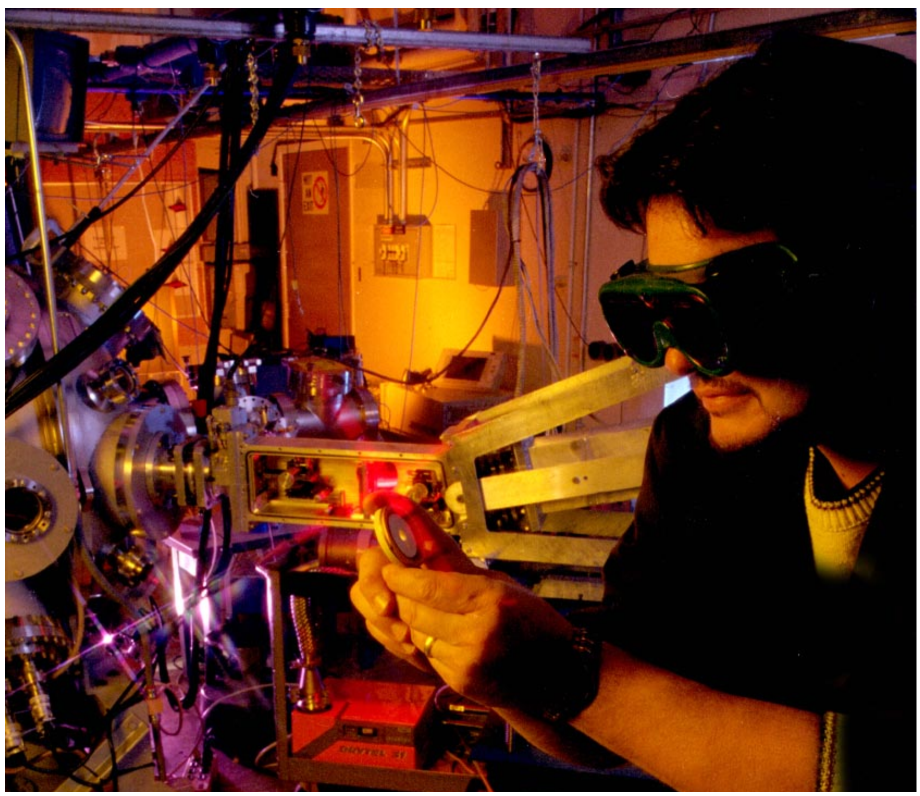


Figure 3. Livermore technician Jim Emig inspects a Livermore-designed spectrometer undergoing calibration with a laser-plasma x-ray monochrometer.

past, the universe expanded more slowly than it does today, implying perhaps the existence of a fifth, repulsive force in nature. But scientists still need to understand the relationship between a Type Ia's luminosity and its light curve shape (the way in which the supernova's brightness changes with time) (Figure 4) in order to rule out other, more mundane possibilities, such as supernovae in the distant past differing from much younger ones that exploded closer to Earth.

Some varieties, known as Type II supernovae, represent the evolutionary endpoint for a massive star, which spends 10 million years burning the hydrogen at its center to iron and then explodes violently in a series of events lasting only a fraction of a second. During the following two to three months, the amount of radiation released from the initial explosion rivals that emitted by the rest of the entire galaxy in which the supernova resides.

In recent years, supernovae have become a major tool for exploring the expansion rate and geometry of the universe. Because of their great luminosity, supernovae are visible at vast cosmological distances. By determining their intrinsic luminosity, astronomers can calculate their distance by measuring the apparent brightness measured through a telescope. And by measuring how fast the supernova and its host galaxy are receding from Earth, astronomers can measure the so-called Hubble constant, which relates recession speed to distance and characterizes the age of the universe.

Eastman and collaborators at Harvard University and Australia's Mount Stromlo Observatory have developed a method for determining the intrinsic luminosity of Type II supernovae explosions using computer models of the emitting gas and

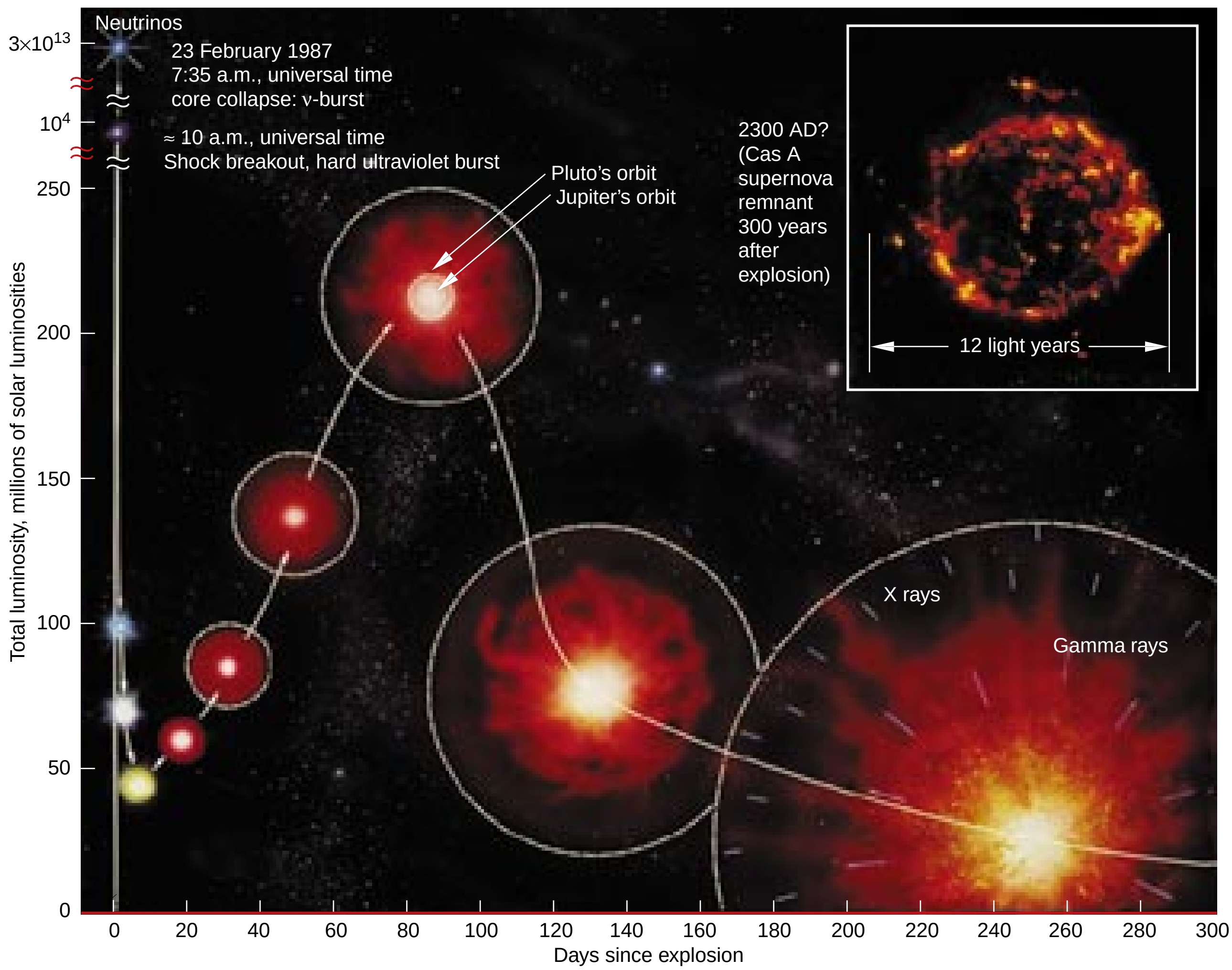


Figure 4. The light curve of a supernova (in this case one that exploded on February 23, 1987) is a measure of its luminosity over the months following its violent explosion. Analyses of light curves help cosmologists determine whether the universe's expansion is speeding up or slowing down.

telescope observations. Their expanding photosphere method is a powerful technique for determining the Hubble constant. Eastman and his colleagues plan to model Springer's experiment with the same code used to model Type II supernovae, thereby determining the accuracy of the code's predictions.

Says Eastman, "The ability to produce, in the laboratory, the same kind of plasma conditions that exist in supernovae will allow both atomic and computational theories to be accurately tested and will provide a firm, experimental foundation for its application to distant supernovae."

Probing the X-Ray Universe

The x-ray universe (wavelengths of 1 to 140 angstroms) features such exotic objects as supernova remnants, x-ray binaries, pulsars, active galaxies, and black holes (Figure 5). Notes Livermore physicist Mark Foord, "X-ray observations allow one to probe into extreme environments in the universe, like conditions found near black holes. We can't get this information from visible light or infrared astronomy."

X-ray spectroscopy, the study of the absorption and emission of x rays, yields significant data on chemical compositions, temperatures, and densities of stellar objects. Livermore has long established itself in the x-ray astronomy community with its expertise in modeling x-ray phenomena and building state-of-the-art diagnostic instruments. Achieving a better understanding of x-ray data is an important goal in stockpile stewardship studies.

With the launch of three major x-ray observatories scheduled to begin during 1999, the astrophysics community will be taking a big step toward understanding the x-ray universe. These spacecraft are NASA's Advanced X-Ray Astrophysics Facility (AXAF), the European Space Agency's X-Ray Multi-Mirror Mission (XMM), and the Japanese Space Science's Astro-E (Figure 6). Livermore researchers helped to build a spectrometer grating for the XMM, and they will be working with colleagues at NASA and U.S. and European universities to analyze data from the AXAF.

The new spacecraft will provide a more than 10-fold improvement in sensitivity and resolution and will send

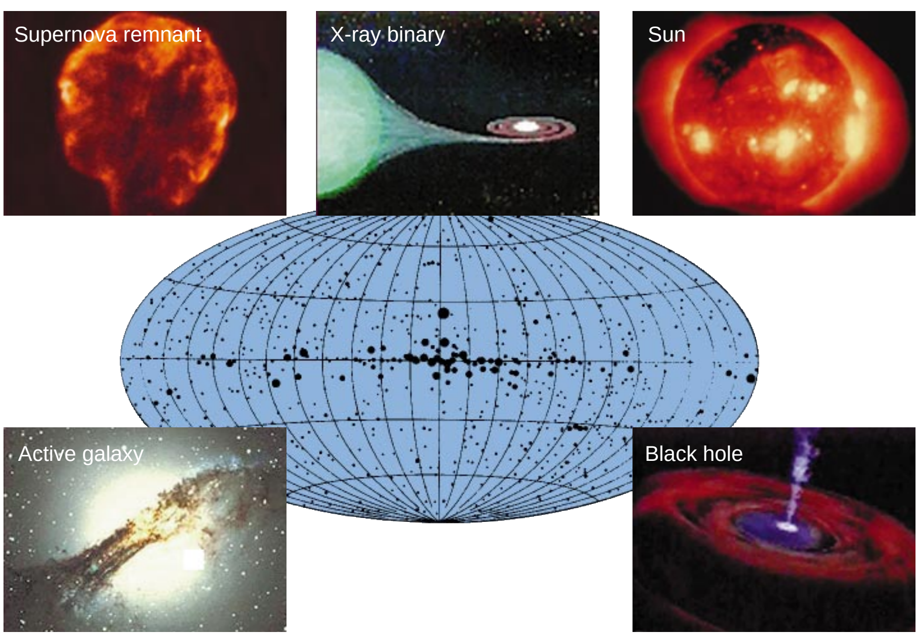


Figure 5. The x-ray universe includes exotic objects such as supernovae remnants, x-ray binaries, pulsars, active galaxies, and black holes.

Figure 6. Data from three x-ray space telescopes will provide a more than 10-fold improvement in sensitivity and resolution.

back a wealth of new information about the x-ray universe akin to that about visible light radiation provided by NASA's Hubble Telescope. "The level of detail contained in these data will provide a major challenge to our analytical capabilities," says Livermore astrophysicist Duane Liedahl, because current computer models often yield widely different interpretations of data from x-ray satellites. The cause, as with the predecessors to OPAL, is oversimplified treatments of atomic structure.

In response to the need for a more detailed and comprehensive model of x-ray phenomena, Liedahl and coworkers Kevin Fournier and Christopher Mauche have developed the Livermore X-Ray Spectral Synthesizer (LXSS) (Figure 7). "We've been working on the model since 1990 in anticipation of these launches," Liedahl says. "We expect that LXSS will play a key role in analyzing the new x-ray satellite data."

This code was designed to interpret data from what astrophysicists call accretion disks. One such x-ray source is a binary star system, in which the higher mass star eventually becomes a compact object, either a white dwarf star, a neutron star, or a black hole. The lower mass star may be so close to the compact star that its outer atmosphere begins to heat up and fall onto the compact star. This reaction generates x-rays that photoionize the gas surrounding the binary system. When the ionized gas transitions back to a more favorable energy state, it generates x rays, which are picked up by astronomical observatories.

Data from LXSS have been successfully tested in laboratory experiments, but the experiments could not realistically duplicate the plasma conditions found in accretion-powered x-ray sources. By using Sandia's new Z-Machine, Livermore researchers plan, for the first time, to create plasmas photoionized with x rays, characterize them, and compare the results to those predicted by LXSS. The Livermore experiments, planned for this summer, will use the Z-Machine's x rays to study the photoionization of iron, an important element that is key to understanding the energy balance in many astrophysical x-ray sources.

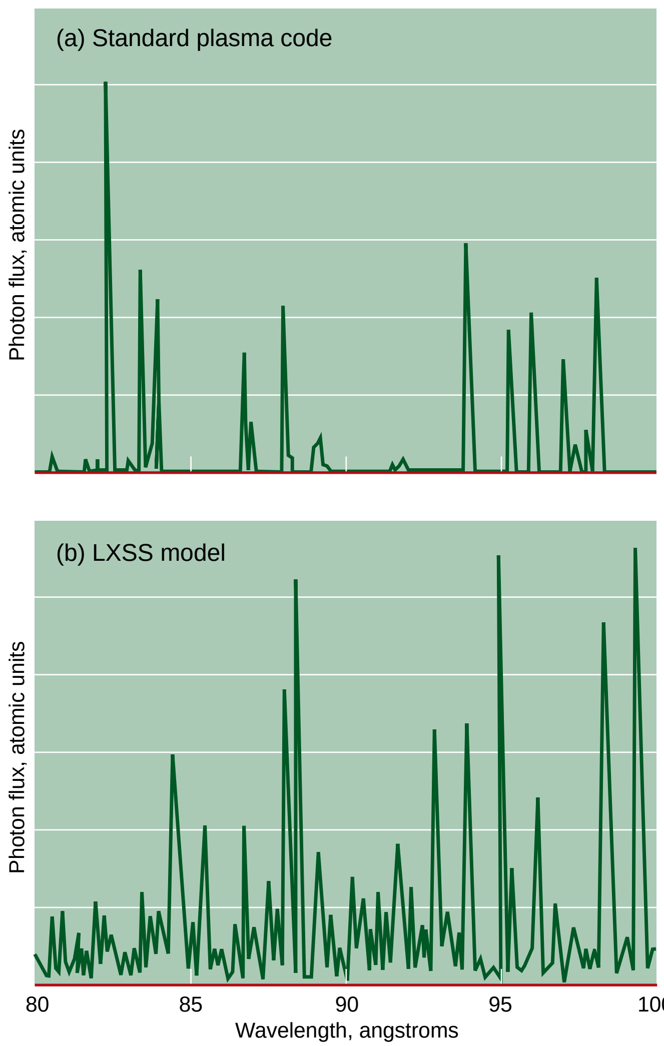


Figure 7. By more accurately predicting the details of intensity (photon flux) versus wavelength, the Livermore X-Ray Spectral Synthesizer (LXSS) code will analyze data from the space telescopes in a far more thorough manner than existing codes.

Explains Foord, "In accretion-powered objects, like binary stars and active galaxies, the x rays are responsible for ionizing the surrounding gas. In typical laboratory experiments, ionization occurs because of electron collisions, a fundamentally different process. Until now, we have not had facilities that could create the sufficient x-ray fluxes needed to reach astrophysical conditions." He says that calculations using Livermore's LASNEX code indicate Z-Machine's radiation fluxes will photoionize samples into astrophysically relevant regimes.

Liedahl notes that LXSS will be used on NIF experiments to help characterize plasmas created by the giant laser. "We intend to keep building on the code to make it as versatile as possible," he says. (See also the December 1997 *Science & Technology Review*, "Marrying Astrophysics with the Earth," p. 21.)

Deepening Our Understanding

The experiments re-creating stellar plasmas are sure to have a lasting effect on a variety of research communities. For astrophysicists, the experiments are validating codes and deepening the understanding of stars to help answer the most basic questions about the nature and evolution of the universe.

For DOE's Stockpile Stewardship Program, the experiments are strengthening fundamental knowledge of atomic processes in extreme environments and providing greater confidence in the computational tools needed to maintain America's nuclear forces. Greater understanding of opacity, for example, will help guide experiments planned on NIF for both stockpile stewardship and inertial confinement fusion.

"We'll be using the same people, facilities, and equipment on NIF that we use for the pulsed-power experiments," says Springer. He notes that NIF will be able to duplicate the stellar regimes created at Sandia's facilities—"and so much more."

Springer also points out that the Laboratory's astrophysical research is attractive to individuals considering a career at Livermore. For example, Robert Heeter, a postdoctoral physicist from Princeton University, will be leading the x-ray experiment effort this summer as part of the new Lawrence Livermore Fellowship Program to attract promising recent graduates.

At least for the next few years, the skies will continue to be an important source of data as well as inspiration for Livermore researchers.

—Arnie Heller

Key Words: accretion, Accelerated Strategic Computing Initiative (ASCI), Advanced X-Ray Astrophysics Facility (AXAF), Astro-E, astrophysics, binary star, cepheids, hohlraum, Hubble constant, iron, Livermore X-Ray Spectral Synthesizer (LXSS), National Ignition Facility (NIF), Nova, OPAL code, opacity, plasmas, Saturn facility, Stockpile Stewardship Program, supernovae, white dwarf, x-ray astronomy, X-Ray Multi-Mirror Mission (XMM), x-ray spectroscopy, Z-Machine.

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About the Scientist

PAUL SPRINGER holds a B.S. in physics from the University of California at San Diego and a Ph.D. in nuclear physics from Princeton University. He joined Lawrence Livermore in 1984 as a physicist in the Nuclear Chemistry Division while working on his thesis project, a measurement of the neutrino mass. He is currently leader of the Experiments Group and associate Physical Database Research Program leader in V Division of the Physics Directorate. He is the author or coauthor of many journal articles and presentations on high-energy-density plasma physics research. He has received numerous honors and awards, including the Department of Energy's Weapons Recognition of Excellence Award in 1994 and 1997 and a 1994 and 1996 Distinguished Achievement Award from the Physics and Space Technology Directorate. Current research interests include high-temperature plasmas, atomic processes in plasmas, astrophysics, x-ray spectroscopy, atomic physics, and neutrino physics.